

# Remote Thermal Sensing Diode Selection Guide

## 1 Preface

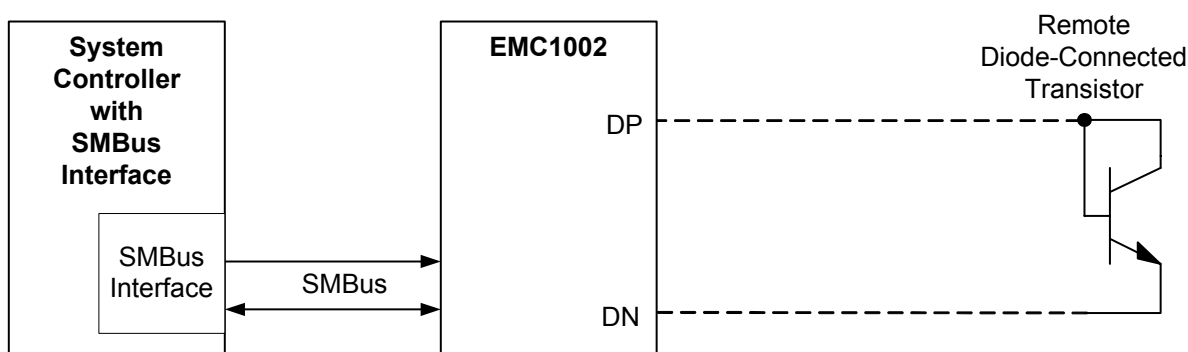
This application note provides guidance to designers of systems that use thermal sensors with remote diodes. A discrete bipolar junction transistor (BJT) is commonly used as the remote diode. This application note provides guidance for selecting a transistor that will be used with an SMSC thermal sensor, such as the EMC1002. SMSC supplies temperature sensors designed to work specifically with CPU thermal diodes, but that is not the subject of this application note. Throughout this document, the phrase 'remote diode-connected transistor' refers to a discrete, diode-connected (Base-Collector junction shorted) BJT.

## 2 Audience

This application note assumes that the reader has previous knowledge of how temperature sensing is performed using diode-connected transistors.

## 3 Overview

The information presented is intended to help in the selection of a remote diode-connected transistor that is used with a thermal sensor as shown in [Figure 3.1](#) below. The application note discusses the semiconductor parameters of the transistor that affect accuracy of the temperature measurement. Because so many transistors are available, it is unrealistic to publish a complete list of all acceptable and qualified devices. This application note does include a table of qualified discrete 2N3904 NPN transistors, but it is not the definitive or complete set of acceptable BJT's to be used in temperature sensing applications.



**Figure 3.1 Block Diagram of a Typical Temperature Sensing System**

## 4 Diode Parameters

Three semiconductor parameters of primary concern when using diode-connected transistors in temperature sensing applications are:

1. Ideality Factor ( $\eta$ )
2. Forward Current Gain (beta or  $h_{FE}$ )
3. Series Resistance ( $R_S$ )

### 4.1 Ideality Factor ( $\eta$ )

The ideality factor is a parameter in the diode current-voltage relationship. It approaches a value of 1.0 when carrier diffusion dominates current flow, and approaches 2.0 when recombination current dominates. This term is a constant for any particular device though it can vary between individual devices.

Temperature sensors are calibrated during final test to provide accurate readings with a diode that has a typical ideality factor. This value is referenced as  $\eta_{ASSUMED}$  in the following discussion. The ideality factor of the user's diode-connected transistor will be referenced as  $\eta_{REAL}$ .

The temperature measured by a temperature sensor will include an error from the real temperature as defined by the equation in [Figure 4.1](#). Use of this equation requires that temperatures be converted to Kelvin temperature. It is not correct if used with a temperature in Celsius or Fahrenheit.

$$T_{MEASURED} = \frac{\eta_{REAL}}{\eta_{ASSUMED}} \bullet T_{REAL}$$

**Figure 4.1 Temperature Error Due to Ideality Factor Mis-match**

SMSC recommends the use of a 2N3904 transistor as the remote diode. The ideality factor is typically not presented in the transistor datasheet. SMSC has measured several samples of each of the transistors listed in [Table 5.1](#) and determined that the ideality factor is ~1.004. Other transistor devices may be used, but should be qualified<sup>1</sup>.

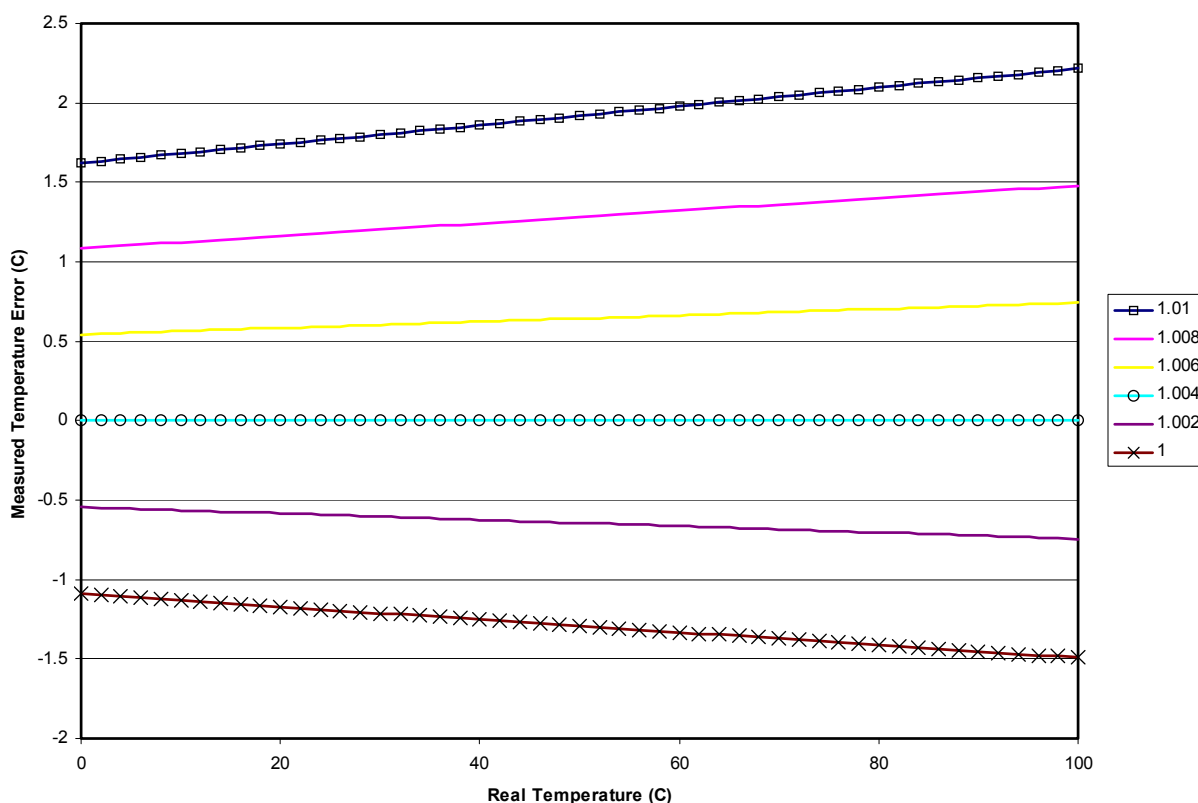
**Table 4.1 Typical Ideality Factors for 2N3904 Diode-Connected Transistors**

MANUFACTURER	TYPICAL IDEALITY FACTOR
Rohm	1.0038
Diode Inc	1.0044
Philips	1.0049
ST Micro	1.0045
ON Semi	1.0046
Chenmko	1.0040
Infineon	1.0044
Fairchild	1.0046
National	1.0037

1. Qualification of these devices is ideally performed by obtaining data on the parameters described in this application note from the device manufacturer. Precision thermal equipment is required to measure the parameters. Please contact your SMSC Field Applications Engineer for additional support.

In the previous equation, the ideality factor that the temperature sensor is calibrated for is  $\eta_{\text{ASSUMED}}$  and the actual ideality factor of the diode-connected transistor is  $\eta_{\text{REAL}}$ . As can be seen from the equation, the temperature measurement error is not a constant offset, but increases as  $T_{\text{REAL}}$ , the temperature of the remote diode-connected transistor, increases.

Figure 4.2 shows the temperature measurement error induced solely from the differences between  $\eta_{\text{ASSUMED}}$  and  $\eta_{\text{REAL}}$ . In this figure,  $\eta_{\text{ASSUMED}}$  is 1.004, a typical ideality factor value for a 2N3904 NPN diode-connected transistor. Temperature sensors are typically calibrated in the range of the 2N3904 (1.004) because this is also very similar to the ideality factor of a majority of substrate diode-connected transistors found on CPU's and GPU's.

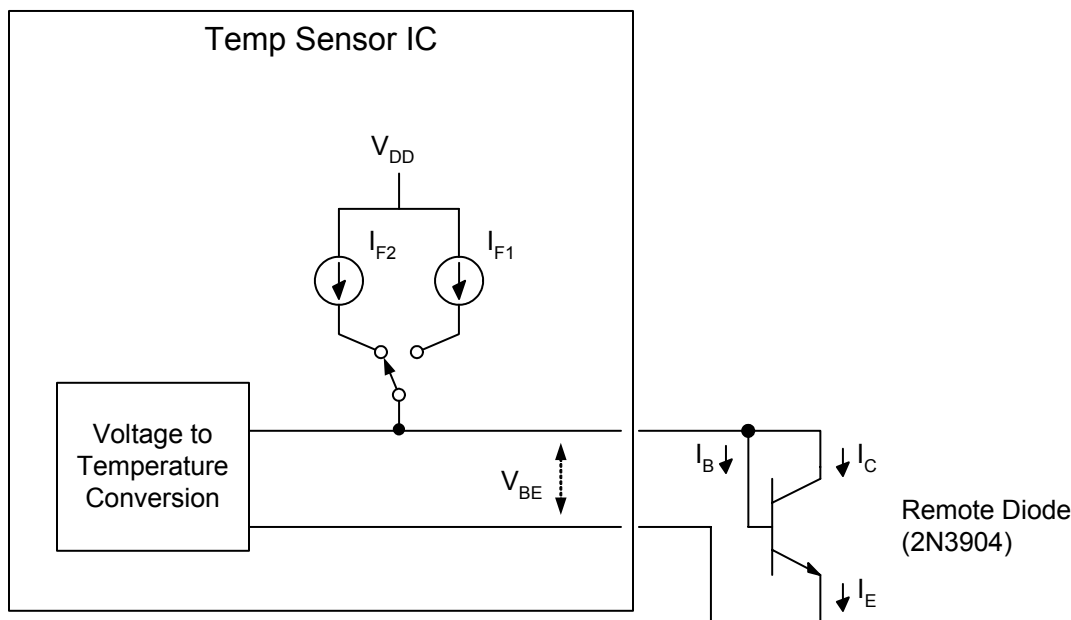


**Figure 4.2 Temperature Error Vs. Ideality Factor of Diode (with IC trimmed to 1.004)**

Figure 4.2 can also be used to explain why true 2-terminal discrete diodes are not used in temperature sensing applications instead of 3-terminal devices such as the 2N3904. A discrete 2-terminal diode, ideally, would perform fine in temperature sensing applications as a thermal diode. From characterization in SMSC labs, it has been found that discrete 2-terminal diodes typically have an ideality factor much higher (1.2-1.5) than  $\eta_{\text{ASSUMED}}$  of 1.004. This discrepancy between  $\eta_{\text{ASSUMED}}$  and  $\eta_{\text{REAL}}$  would cause unacceptable temperature measurement errors at all temperatures.

## 4.2 Forward Current Gain (beta)

A typical temperature sensor forces two fixed currents ( $I_{F1}$  and  $I_{F2}$ ) into the thermal diode to measure temperature as shown in [Figure 4.3](#) below.



**Figure 4.3 Two Current Sources**

The temperature sensor measures the voltage,  $V_{BE}$  which is developed is based on the collector current; not the emitter current.

$$T = \frac{(V_{BE2} - V_{BE1}) * q}{\eta k * \ln \left( \frac{I_{C2}}{I_{C1}} \right)}$$

**Figure 4.4 Ideal Diode Equation**

The forward current gain (beta) of a transistor is not a constant over all operating conditions, but varies over temperature and as a function of  $I_C$ . The variation in beta over temperature does not induce temperature measurement error. However, if the transistor has a large variation in beta as a function of  $I_C$ , the temperature reading can be inaccurate due to beta induced error.

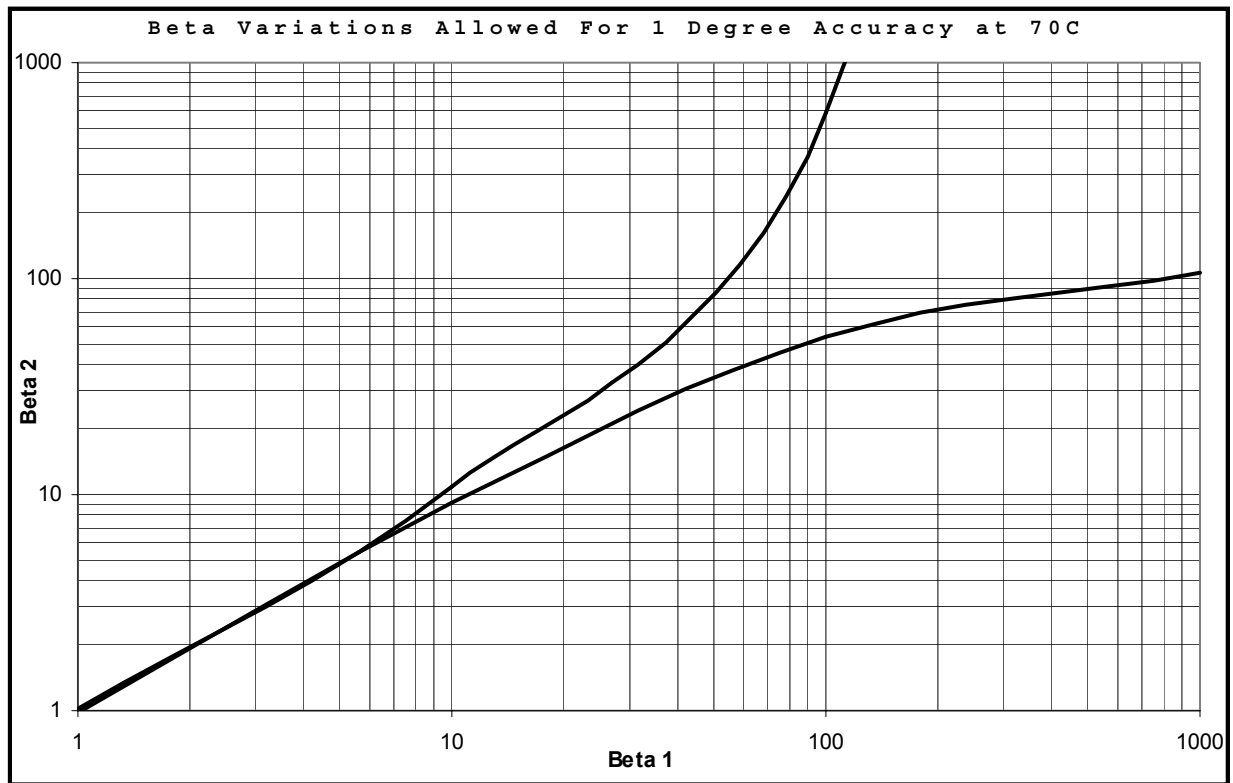
If the value of beta is relatively constant over the range of forced emitter currents, then the ratio of  $I_{C2}:I_{C1}$  remains equal to the ratio of the two forced emitter currents and induces no error. It only becomes a problem when the beta variation causes the  $I_{C2}:I_{C1}$  ratio to not match the  $I_{E2}:I_{E1}$  ratio.

The equation in [Figure 4.5](#) shows the error induced from a non-constant value of beta at the two currents.  $\beta_{F1}$  represents the beta of the transistor at the current value  $I_{F1}$  while  $\beta_{F2}$  represents the beta at the current value  $I_{F2}$ . 'N' represents the fixed ratio of the two forced ( $I_{E1}$  and  $I_{E2}$ ) currents. If beta is constant over the range of the two currents ( $\beta_{F1}=\beta_{F2}$ ), then there is no temperature measurement error induced because of beta variation.

$$\Delta T_{ERROR} = T_{REAL} \cdot \left( \frac{\ln \left( \frac{\beta_{F2} \cdot (1 + \beta_{F1})}{\beta_{F1} \cdot (1 + \beta_{F2})} \right)}{\ln(N)} \right)$$

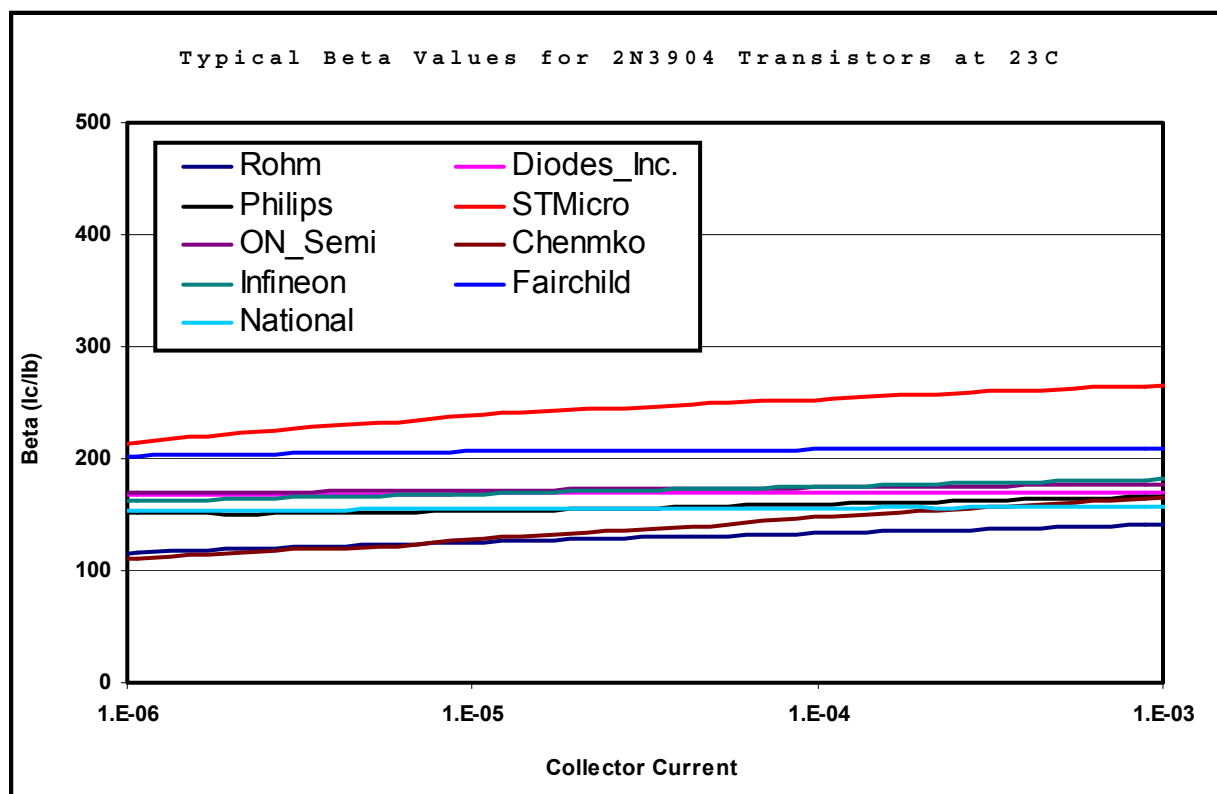
**Figure 4.5 Temperature Error Due to beta Variation Equation**

Figure 4.6 presents a plot of allowable beta variation over the sensor's sourced current range (10 - 400uA) to be able to still maintain at least 1 degree accuracy at 70C. The beta of the transistor must reside between the two lines in the plot, over the extremes of the current range of the temperature sensor, in order to maintain 1C accuracy with the selected diode-connected transistor. The x-axis represents the beta of the diode connected transistor at  $I_{F1}$ , while the y-axis is for the beta at  $I_{F2}$ . varies over the sensor's sourced current range.



**Figure 4.6 Allowed Beta Variation**

Figure 4.7 shows 'typical' values of transistor beta for a limited sample of these devices. These devices were characterized in SMSC characterization labs. This data is not to be used as a guaranteed value for the specific transistor, it is purely a typical representation for the limited quantity tested by SMSC.



**Figure 4.7 Typical Beta Values**

The conclusion to draw from [Figure 4.6](#), [Figure 4.7](#) and [Table 4.2](#) is that for the set of 2N3904 transistors tested by SMSC, the beta was consistently high and flat. The measured value of beta easily resides inside the 2 lines of [Figure 4.6](#), over the entire temperature sensor's sourced current range. [Table 4.2](#) quantifies the error induced from beta variation using the 2N3904's tested by SMSC. It should be clearly noticed that with the tested devices, beta variation has a very small effect on temperature measurement accuracy.

**Table 4.2 Temperature Error Due to 2N3904 Beta Variation @70C**

MANUFACTURER	TEMPERATURE ERROR (C)
Rohm	+0.07
Diode Inc	+0.00
Philips	+0.04
ST Micro	+0.03
ON Semi	+0.01
Chenmko	+0.15
Infineon	+0.03
Fairchild	+0.00
National	+0.00

### 4.3 Series Resistance ( $R_S$ )

Series resistance is another parameter that affects temperature measurement accuracy. Series resistance causes the temperature sensor to report the temperature higher than the temperature of the thermal diode really is. The relationship between temperature offset and series resistance is displayed in the following equation.

$$T_{offset} = \left( \frac{q}{\eta k} \right) \frac{(I_{F2} - I_{F1}) R_S}{\ln \left( \frac{I_{F2}}{I_{F1}} \right)}$$

**Figure 4.8 Temperature Offset Error Due to Series Resistance Equation**

The temperature error induced by series resistance is a constant offset for all temperatures. When using a typical SMSC temperature sensor, the magnitudes of  $I_{F2}$  and  $I_{F1}$  induce approximately +0.67C error per Ohm of series resistance. For different 2N3904 devices characterized by SMSC, the  $R_S$  was found to be less than 1 Ohm. This does not include the series resistance due to PCB traces connecting the sensor and remote diode; this only represents the series resistance found in the characterized 2N3904 devices. [Table 4.3](#) quantifies some typical values of series resistance found for a sample of different 2N3904 devices<sup>1</sup>. This value of series resistance for the set of 2N3904's tested was found to have a positive temperature coefficient and as a 'rule-of-thumb', typically increased approximately 5% per 10C increase.

**Table 4.3 Typical Values of Series Resistance for 2N3904 Diode Connected Transistors**

MANUFACTURER	SERIES RESISTANCE( $R_S$ ) @70C IN OHMS
Rohm	0.68
Diode Inc	0.65
Philips	0.72
ST Micro	0.58
ON Semi	0.90
Chenmko	0.73
Infineon	0.57
Fairchild	0.60
National	0.51

## 5 Tested Diode List

This table lists a limited selection of 2N3904 NPN transistors that have been characterized in SMSC laboratories and found to meet the specifications to obtain 1C accurate measurements.

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1. [Table 4.3](#) should NOT be used as a guideline for offsetting the temperature reported by an SMSC temperature sensor. SMSC temperature sensors are typically calibrated using a 2N3904 diode-connected transistor which already compensates for this series resistance error term. [Table 4.3](#) is presented as a reference to help thermal designers understand the possible effects of non-idealities in temperature measurement.

**Table 5.1 Tested Diodes for Temperature Sensing Applications**

MANUFACTURER	MODEL NUMBER
Rohm	UMT3904
Diodes Inc	MMBT3904-7
Philips	MMBT3904
ST Micro	MMBT3904
ON Semiconductor	MMBT3904LT1
Chenmko	MMBT3904
Infineon Technologies	SMBT3904E6327
Fairchild Semiconductor	MMBT3904FSCT
National Semiconductor	MMBT3904N623

## 6 Conclusions

In conclusion, while differences were seen between different manufacturer's versions of 2N3904 BJT's, the results when using them with SMSC temperature sensors were very consistent. For all typical 2N3904 devices tested, temperature never varied more than +/-0.2C from the true temperature. The 2N3904 devices listed in Table 5.1 (or any BJT/diode with equivalent parameters) will yield accurate temperature measurement results when used with SMSC temperature sensors.

SMSC supplies a family of temperature sensors for many applications. Several special functions, such as resistance error correction and ideality configuration are available. In addition, some devices are designed to work specifically with CPU thermal diodes. Please consult your SMSC representative or [www.smisc.com](http://www.smisc.com) for additional information.





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